Endoscope Illumination and Light Pipes with FRED White Paper

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In illumination design one of the main challenges for the illumination designer is to capture as much light from the source and get it "optically plumbed" to the illumination plane with the correct spatial and angular distribution. In the design of medical and industrial endoscopes the illumination designer is trying to meet these typical illumination design goals. Often the light from a HID or tungsten filament lamp and an elliptical reflector is imaged into a fiber optics bundle and the output of the fiber bundle is imaged into five endoscope illumination fiber bundles. These five illumination fiber bundles are often arranged in a circle around the periphery of the center imaging fiber bundle, see Figure 1.

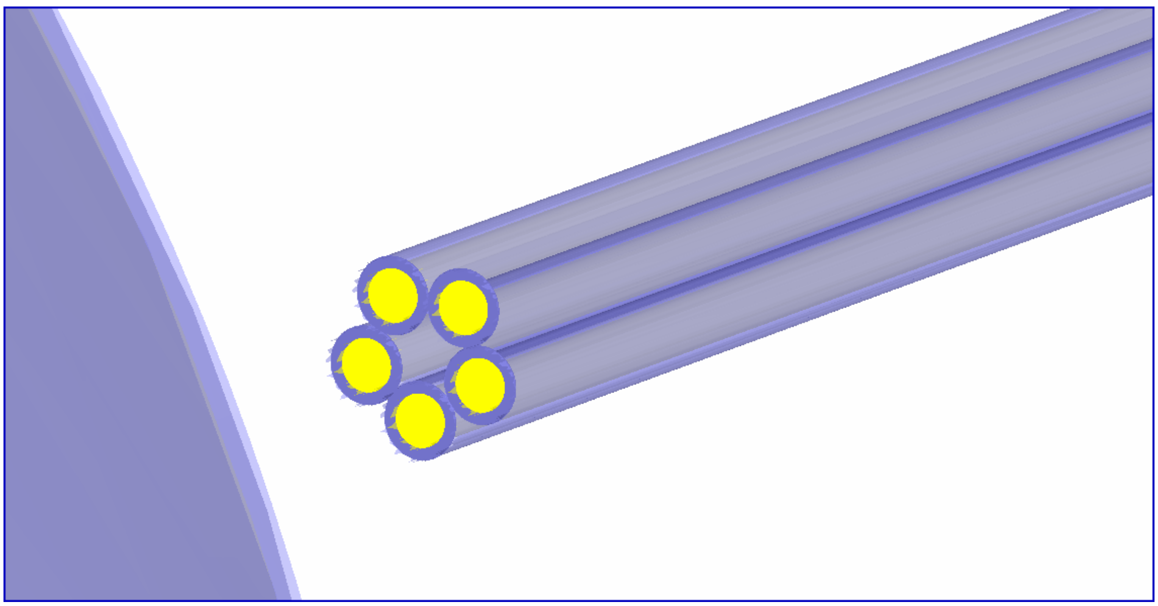

Figure 1. Five Endoscope Illumination Fibers

One of the problems of doing the illumination analysis of light collection by the imaging lens from the single fiber into these five endoscope illumination fibers is adjusting the five fibers and each of their respective claddings along the optical axis for each analysis perturbation. For each illumination analysis of the collected irradiance ten objects (five fibers and five claddings) have to be moved to the next analysis location along the optical axis along with the detector and any blocking apertures. This is quite an optical entourage to move every time for each illumination analysis. FRED's scripting language to the rescue.

FRED has a scripting language that helps automate this task and to make this optical engineering program extremely powerful in the hands of illumination designers and optical engineers who take the time to learn how to exploit this inherent power. FRED's scripting language is Basic complied scripting language with Basic like commands, data structures, functions, and subroutines. The data structures enable users to access every object, surface parameter, and property. The functions and subroutines enable us to interactively change the surface parameters and object properties based upon the calculations performed within the subroutines. Let's take a look at an auto focus script for finding the highest irradiance for these ten objects in our endoscope illumination analysis problem.

FRED Auto Focus Script Example

```
'autofocus by changing detector position and lens parameters while monitoring total power or irradiance on detector for max
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'declarations
Dim op As T_OPERATION
Dim an As T_ANALYSIS
Dim zposn As Long, detNode As Long, count As Long, maxzposn As Long, steps As Lon
Dim irrad As Double, pwr As Double, maxpwr As Double

'find detector node
detNode = FindFullName( "Geometry.Detector 1")
Print "Found detector at node " & detNode
detNode = FindFullName( "Geometry.Detector 1.Det 1")
Print "Found detector surface at node " & detNode

'Print out focus location and irradiance or total power
i = GetTextCurCol : j = GetTextCurRow
SetTextPosition j, i+3 : Print "Det1 Z Posn " : SetTextPosition j, i+5 : Print "Irradiance or Total Pwr"

Print "detNode = " & detNode
GetOperation 5, 1, op
zposn = op.val3

an.posZ = zposn

Print "ZPosn = " & zposn
Print "an.posZ = " & an.posZ

'set light source and get ready to trace new rays and find the current irradiance or total power on detector in starting zposn
Update
DeleteRays
CreateSources
TraceExistingDraw
pwr = GetSurfIncidentPower (6)    'surface node number must be on detector surf with analysis surf
maxpwr = 0
maxzposn = 0

Print "Power on Surf = " & pwr

steps = 11
zstep = zposn * 0.05
zposn = zposn * 0.75

For i = 0 To steps-1
        'move the detector
        zposn = zposn + zstep
        op.val3 = zposn
        SetOperation 5, 1, op

        'ray trace with new det posn
        DeleteRays
        CreateSources
        TraceExistingDraw

        'get power on det in new pos and compare
        pwr = GetSurfIncidentPower (6)

        Print "Focus is at Z = " & zposn & " with Power = " & pwr
        Print "max power is = " & maxpwr & " power = " & pwr
        If pwr > maxpwr Then
                Print "in the loop"
```

```
                maxpwr = pwr
                Print "maxpwr = " & maxpwr
                maxzposn = zposn
                Print "maxzposn = " & maxzposn
        End If

Next

Print "Best Focus is at Z = " & maxzposn & " with Maximum Power = " & maxpwr
op.val3 = maxzposn
SetOperation 5, 1, op
Print "Set new detector to max power location of Z = " & maxzposn
Print"Stop of new script run "
```

This script shows lots of printed information to help the user in debugging the script and also to label the output for easy interpretation and quantitative analysis. For the zooming of the detector we need to get the full name and node number in the list of nodes in the optical system prescription. In the next section we format the labels and data output so that we can get a tabular output on the screen during the script run as the detector is zoomed through focus and the irradiance is calculated. This makes reading and interpreting that data very easy and error free.

Next we update the design and tell FRED to delete any existing rays in the database and find all the sources to trace rays from and then to trace these rays. After the first ray trace we ask FRED to get the power on the detector in the starting position so we can know if succeeding detector positions have a higher or lower irradiance.

Finally we enter the loop and move the detector by step increments and then perform another ray trace and detector irradiance calculation. After traversing the full distance of the zoom range we exit the loop and print the location and magnitude of the highest irradiance. We can decide if we want to accept the current maximum or move the zoom range and auto focus again about a new optical axis location.

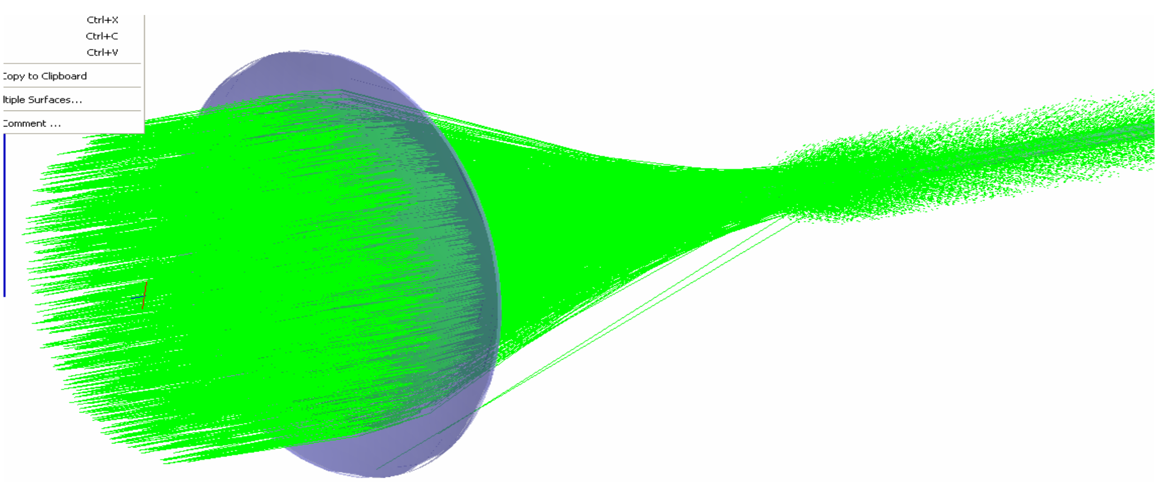

Figure 2. Source Rays with Condenser Lens into Illumination Fibers

Best Focus Found – Now Locate Illumination Fibers and Analyze Illuminance

Now that we found the best focus with the script above we can locate the input end of the illumination fibers at this location and determine how much light will exit these endoscope fibers at the end to illuminate the analysis or operation to be performed. In

Figure 2, above we can see the input end of the illumination fibers are overfilled by the condenser lens. Some of the light enters the illumination fibers and is propagated down these fibers and eventually exit the distal end of the fibers and illuminate the operation area. We can see the rays exiting the distal end of the fibers in Figure 3 and being absorbed by an analysis detector.

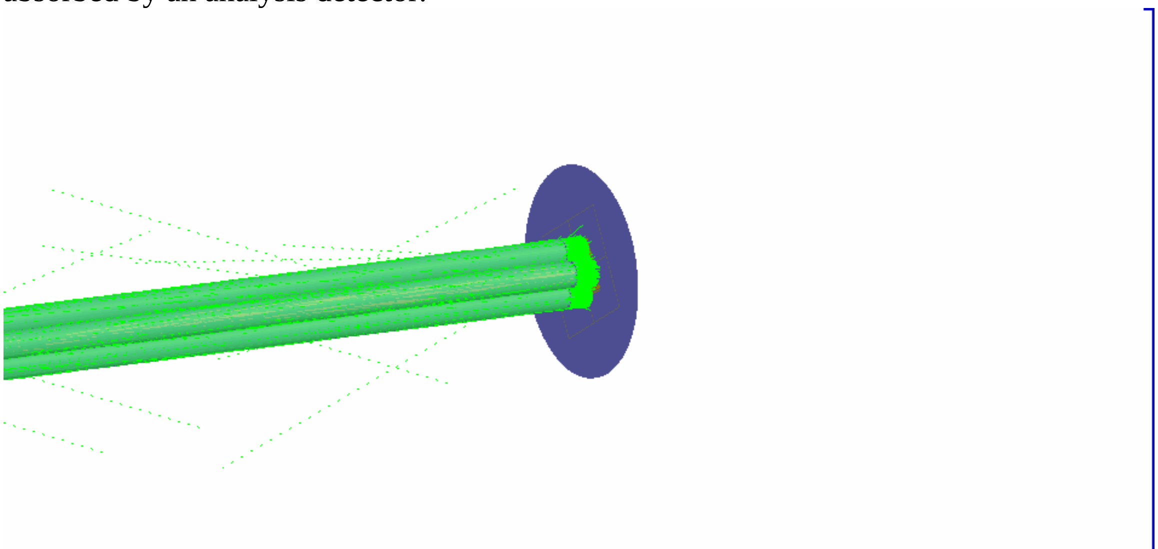

Figure 3. Exit End of Illumination Fibers with Illumination Rays

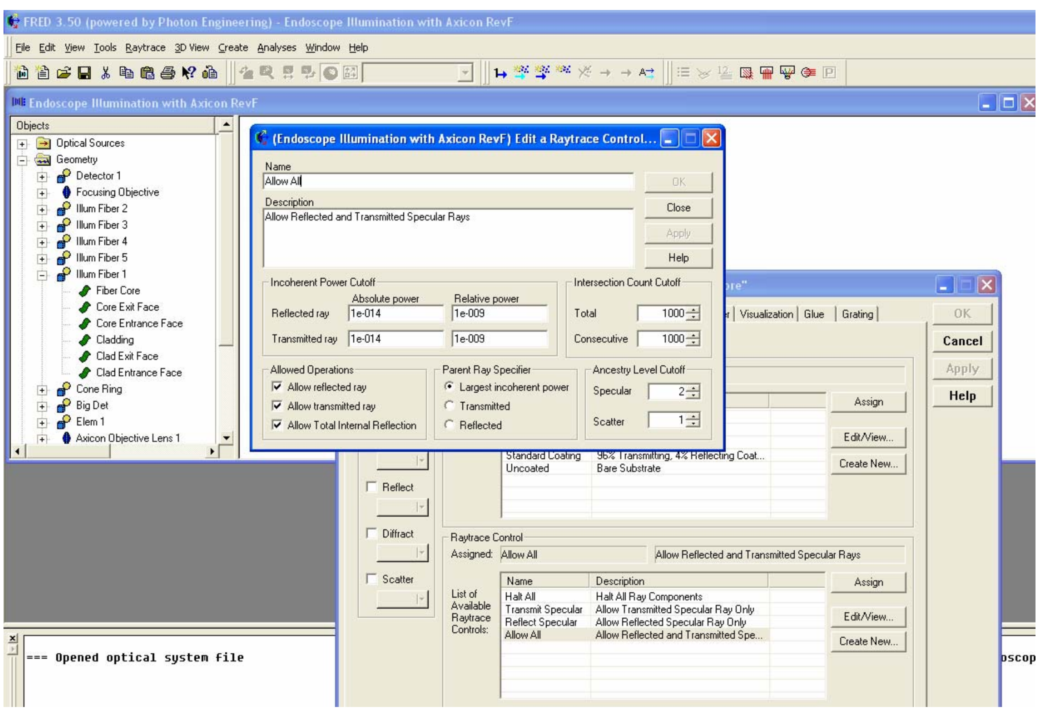

Figure 4. FRED Ray Tracing Control Criteria

As you might guess in a light pipe or illumination fiber there are going to be quite a few reflections or TIR's (total internal reflections), especially in these five long illumination fibers. FRED has some powerful ray trace controls to help minimize errors or maximize your analysis capabilities. There are several criteria that can be applied to a ray as it is traced through a light pipe or optical system. The first as seen in Figure 4 above is the relative or absolute power of the ray. The second method is by the ray intersection count cutoff and this particular control method may need to be increased when an illumination designer wants to propagate rays down a long fiber or light pipe for analysis. Finally the number of ancestry levels can be used to control a ray's propagation. The ancestry levels can be specified by stopping the ray if more than a certain number of reflections take place where the ray is split off, or by the number of scatters that take place where the ray is split off.

So we have grabbed the rays with our condenser lens and got them into the fiber and propagated them down or illumination fibers to the detector at the working end of the scope and now we find out that we did not collect enough light to satisfy our specification. Instead of illumination these fibers with a disc of light why don't we illuminate them with a ring of light? Easier said than done unless you have a powerful optical engineering software tool like FRED to help turn your illumination dreams into reality. A little bit of Aerosmith's Dream On certainly helps with the creativity too.

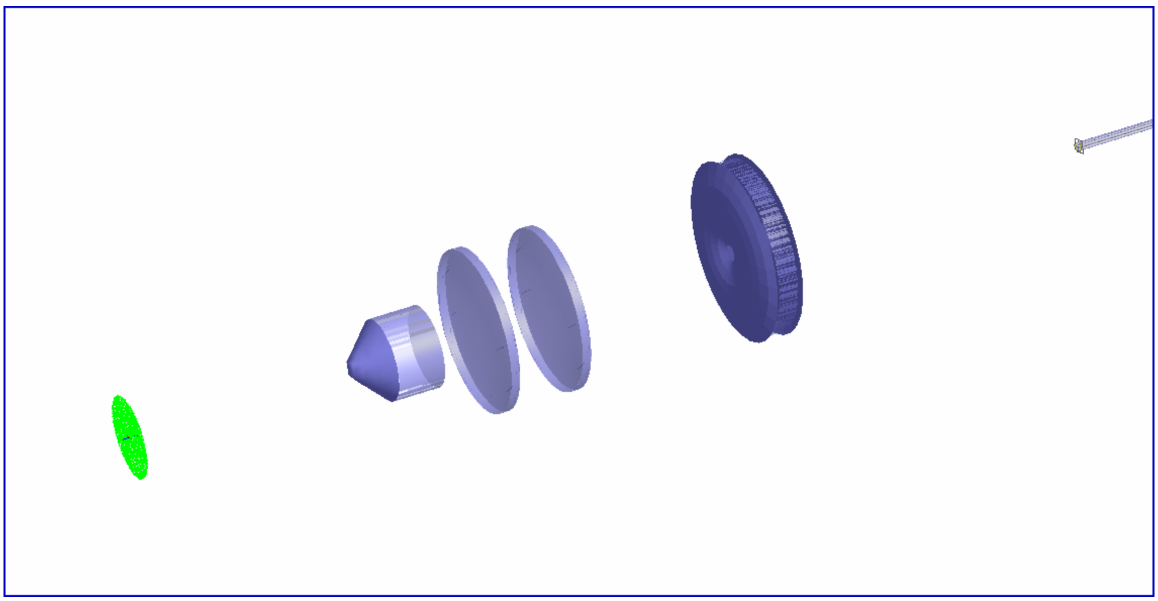

Figure 5. Axicon and Toroid's for Ring Illumination System

To form a ring illumination on these fibers we can use a refractive axicon lens to take the light from our collimated source and diverge it into an annulus of irradiance. Next we will use two biconvex lenses as condenser lenses to capture this irradiance and get it steered down the optical axis. Finally we will use a toroid lens with spherical surfaces to image our annulus of irradiance into a ring illumination down at the entrance to the illumination fibers. See Figure 5, above for the optical system layout without rays.

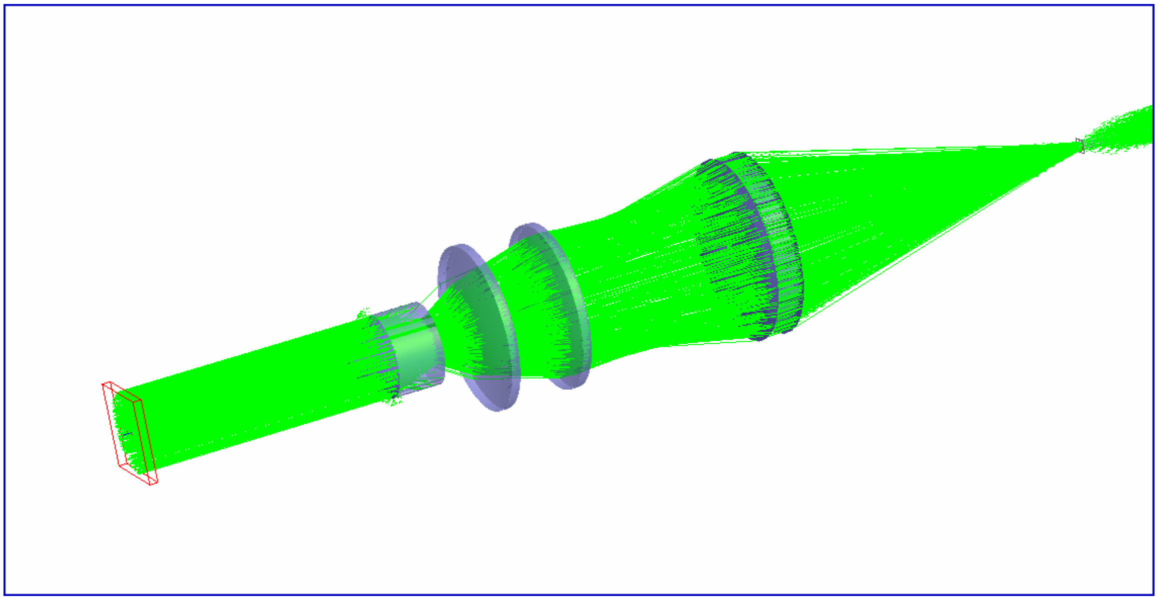

Figure 6. Axicon and Toroid's for Ring Illumination System with Rays

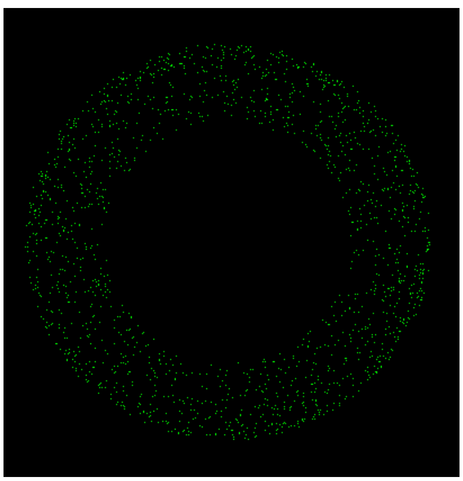

Figure 7. Ring Illumination

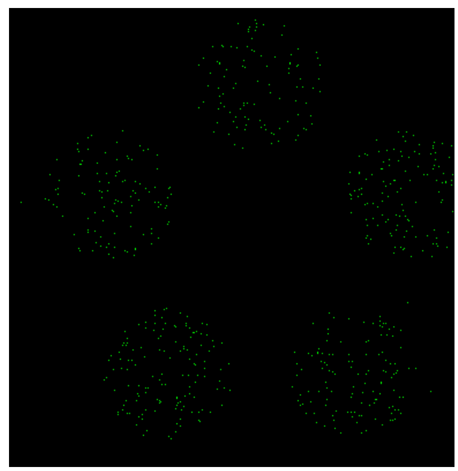

Figure 8. Exit Illumination

We can see the axicon in Figure 6 create the diverging annulus of irradiance from the lamp. We can also see the condenser lenses capturing this light and getting it to the toroid lens for the ring illumination, seen in Figure 7, at the entrance end of the fibers. Because the fibers lie on a ring and the illumination pattern is a ring we have much more of the captured irradiance from the lamp being input into the entrance of the fibers than before. If more illumination goes in then more will come out at the distal end, see Figure 8, for the surgeon to use in the procedure.

Light Pipes and Integrating Rods In FRED

In many illumination designs it is necessary to spatially homogenize or uniform the light gathered from a lamp and this is achieved by a light pipe or integrating rod. In simple terms the longer the rod the more internal reflections take place and the more spatially uniform the irradiance is at the exit of the rod. The more reflections that take place in the rod the more energy is absorbed. With FRED we can take a ray distribution file or a measured or created light source, capture the light and or focus it into the entrance aperture of an integrating rod or light pipe. We can place a detector at the entrance, and exit to investigate the spatial distribution of the light to quantify the performance of the integrating rod. With FRED we can also model the absorption of the coatings, scatter, polarization, and just about any other optical effect that happens to light as it interacts with surfaces.

In Figure 9 below we can see the rays from a mercury lamp with an elliptical reflector being focused into the entrance aperture of an integrating rod and the multiple reflections inside the mirrored rod and the rays exiting the rod with improved spatial uniformity.

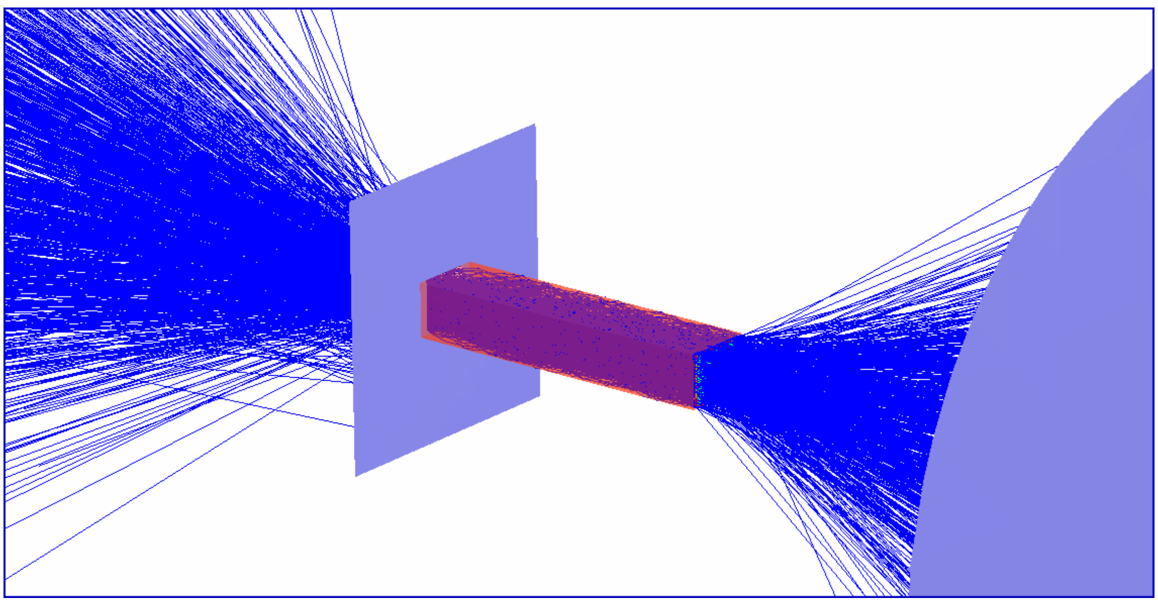

Figure 9. Reflective Integrating Rod Yields Spatially Uniform Irradiance at Exit

Illumination designers often want to investigate many different integrating rod shapes to help achieve the spatial shape and the spatial distribution of light delivered to an illumination plane. FRED gives the illumination designer quite a bit of freedom in the design of light pipe shapes that is really only limited by the designer's imagination and ability to mathematically describe the surfaces and shapes. Of course having the knowledgeable, friendly, willing, and useful help available from the FRED software development team is always reassuring.

In Figure 10 below we can see a twisted light pipe design that is very easy to develop in FRED by specifying the shapes of the entrance and exit apertures which are rectangle in this case. Then the length is specified and the angular twist or rotation is specified in degrees and you will have a twisted light pipe to analyze.

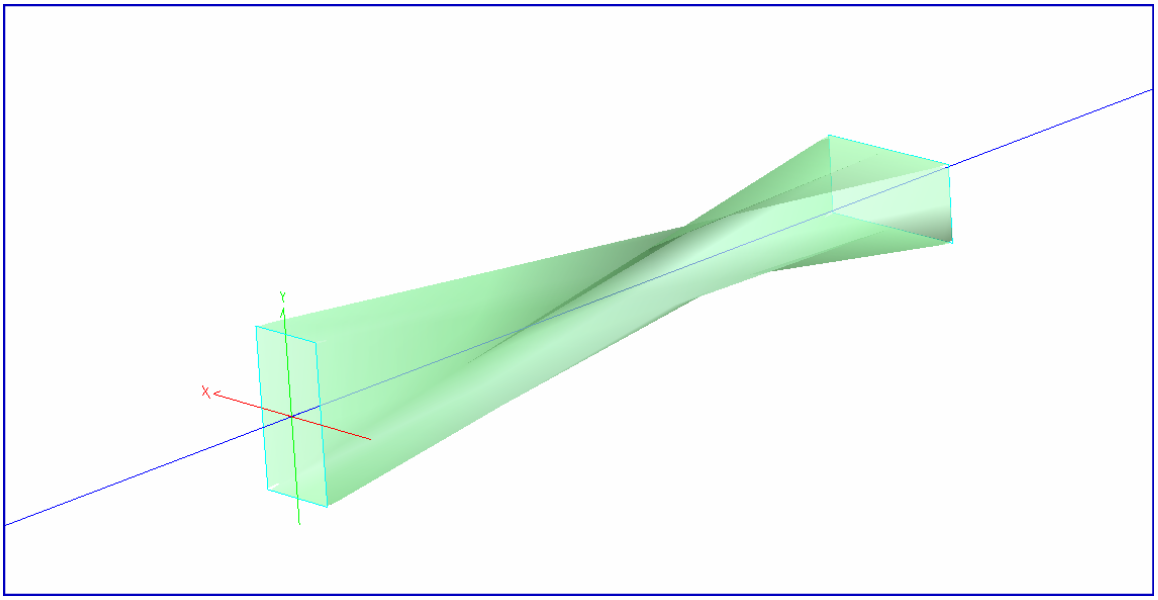

Figure 10. Twisted Light Pipes in FRED

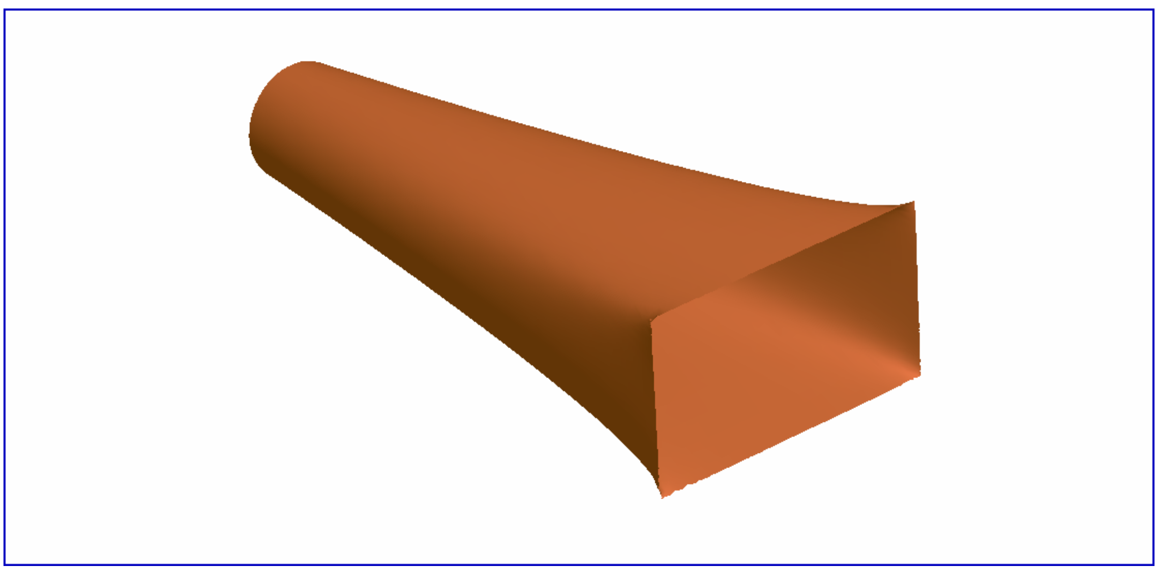

Figure 11. Morphed Light Pipes in FRED

In Figure 11 we have a morphed light pipe where the entrance starts as an ellipse (special case circle) and is morphed to a rectangle with a 16:9 width to height ratio. In this case the morphed light pipe is a hollow reflector intended to be formed by electroformed nickel, but it could easily be changed to a solid light pipe made from glass or plastic material. FRED does not care what the material is, just as long as you can specify the optical properties or use a similar property from one of the catalog materials from one of the many catalogs that come with FRED you will get accurate answers to your analysis questions.

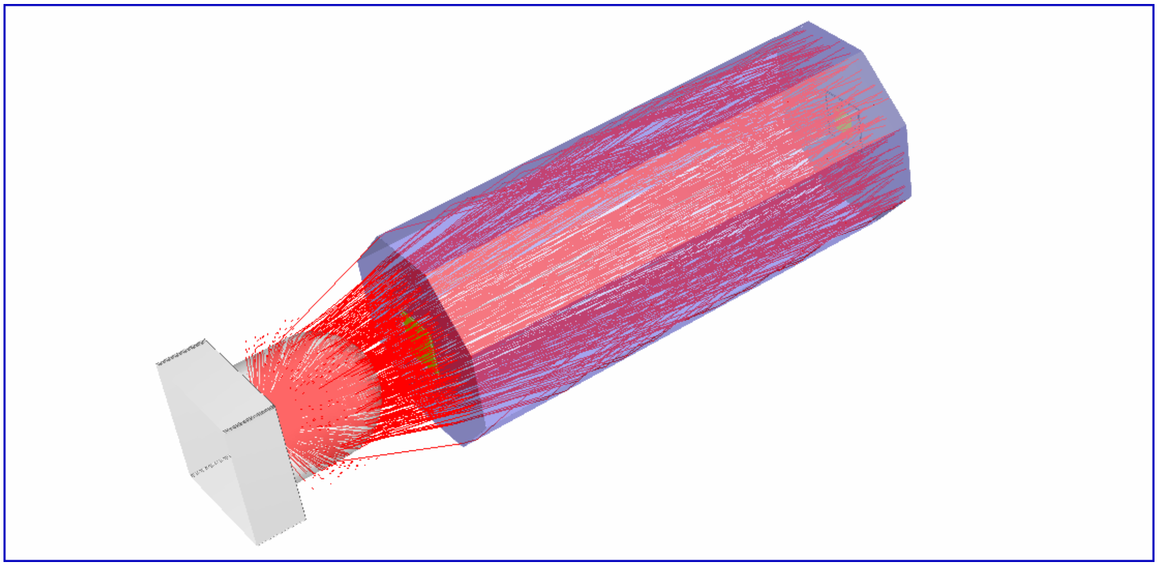

Figure 12. Display Light Pipes Application in FRED with LED Source

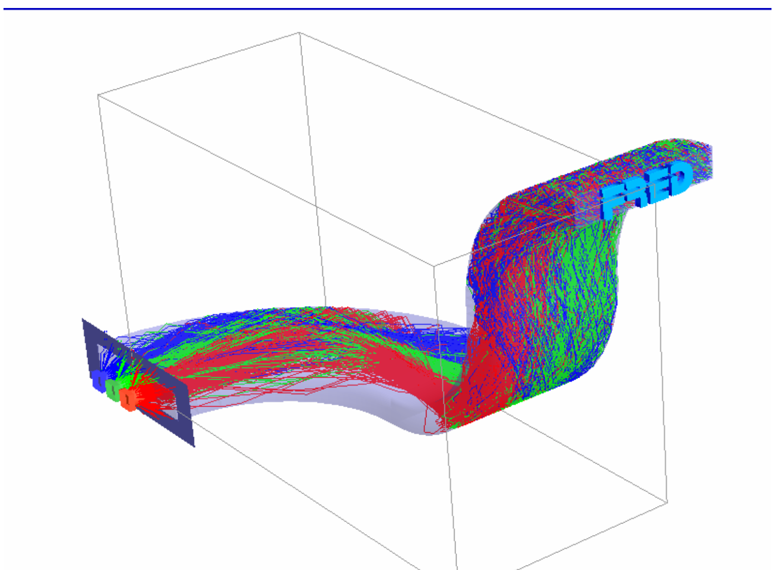

Figure 13. LED's Illuminate Ribbon Light Pipe for Display Application

Figure 12 and 13 are display applications where the illumination from LED's are being routed or piped optically from the source to an illumination plane where they will be viewed by the user. In Figure 14 below we can see a coiled light pipe application where a light pipe or liquid light guide is being coiled to help improve the spatial homogenization of the light source. The multiple reflections inside the light pipe are being modeled properly as is the skew ray propagation to help achieve the spatial redistribution of the light within the light pipe. FRED can use detectors to view and analyze the spatial distribution at the entrance and exit of the light pipes. In Figure 15 we can see one of the special light sources in FRED called a random string. These light sources are very valuable in performing illumination and radiance calculations for self luminous signage applications like EXIT signs.

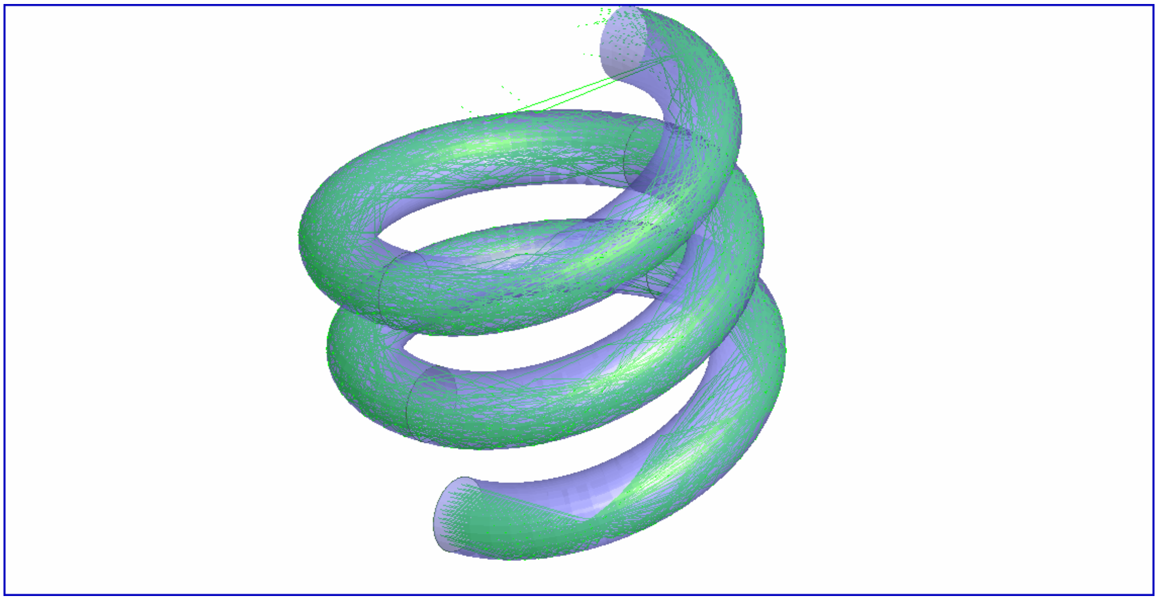

Figure 14. Coiled Light Pipe Created Using Multiple Circular Arc Shapes in FRED

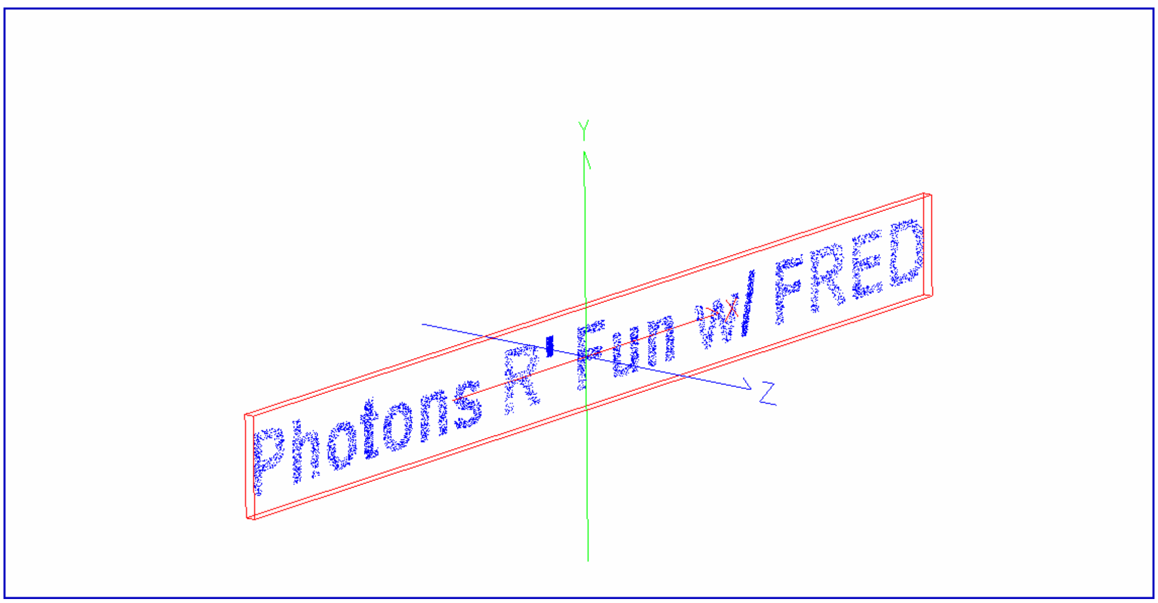

Figure 15. Random String Illumination in FRED for Signage Illumination Analysis

Conclusion:

In this white paper I have tried to demonstrate the inherence raw power and capability of FRED in the areas of illumination design and analysis with special emphasis on light pipes for medical and display applications. The limitations seem to be with the user and their creativity and ability to describe mathematically what geometry they want to model. So put that in your light pipe and propagate it! Using FRED of course.